Certain Factors Limiting the Volume Efficiency of Repeatered Telephone Circuits

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Vacuum tube amplifiers are now regularly built into long distance telephone circuits where required to maintain their volume efficiency. Consequently, the overall volume efficiency of these circuits no longer depends to any important extent on the loss per unit length of the line wires. Instead, the efficiency is controlled by certain factors which, before amplifiers were introduced, had negligible effect. Among these factors are echo, singing or "near singing," and crosstalk. The stability of the lines and amplifiers also becomes very important.

This paper sets forth the methods now in use in the Bell System for computing the highest volume efficiencies at which telephone circuits may be worked without causing echo, singing or crosstalk effects to become too serious. The matter of making proper allowance for the normal variability of the circuits is also included. Specific references are made to various sources of published data which permit the methods to be applied to obtain practical working figures for cable circuits. The fundamentals, however, are also applicable to open-wire circuits.

THE excellence of transmission over a toll telephone circuit is determined by its overall volume efficiency (including the effect of variations from time to time), by distortion of the waves, by various delay effects and by the masking effect of noise. The term "net loss" [1] is commonly used to more specifically designate the overall volume efficiency as limited by the factors which will be discussed herein. It is equal to the total loss introduced by the toll lines and all associated apparatus minus the total gain introduced by all of the amplifiers. In the United States the net loss is usually given for the single frequency of 1,000 cycles and is expressed in decibels.

To avoid producing an undue amount of echo, singing (or near singing), or crosstalk in repeatered circuits, the net loss must be kept above certain minimum figures. The net loss which safely meets requirements for echo, singing and crosstalk after making due allowance for transmission variations in the circuit is called the "minimum working net loss." This paper discusses the methods used in the Bell System for predetermining the minimum working net losses of telephone circuits, particularly those in cable, for which references to published data are made which will enable telephone transmission engineers to readily carry out the required computations.

A telephone circuit may be used for terminal business only (i.e.,

[1] The net loss of a circuit is the insertion loss of the circuit between 600-ohm impedances.

only for calls between the two cities at which it terminates) or for through business (i.e., the circuit may be connected at one or both ends to circuits to other cities). Evidently in the case of circuits used for this second purpose consideration must be given to various combinations of circuits which may be connected together, as dealt with in the paper entitled "General Switching Plan for Telephone Toll Service" by H. S. Osborne (*B. S. T. J.*, Vol. IX, p. 429, July, 1930). Also, the working out of such a plan involves various compromises. While in working out a general transmission plan, consideration must be given to the fact that a given through circuit sometimes appears in one connection and sometimes in another, there is little difference between the computation of the minimum working net loss of a single link connection and the computation for some particular assumed combination of through circuits into a multi-link connection. The discussion which follows is written as if applying particularly to terminal circuits. However, the reader may take the methods as practically applying to a long built-up connection.

The method of determining the echo limitation is to determine the minimum echo net loss [2] and then to add an allowance for variations to determine the minimum working echo net loss. In the case of singing and crosstalk, however, the minimum working net losses are determined directly, allowance for variations being made, respectively, in the singing margin required under average conditions and in the average amount of crosstalk considered allowable. After the minimum working echo, singing and crosstalk net losses have been computed separately, the largest one of the three values is taken as the minimum working net loss of the circuit.

The echo, singing and crosstalk limitations and the normal variations are considered in detail in what follows:

Echoes

In the telephone art, the term "echo" [3] is applied to more or less faithful repetition of the conversation to which the talker or listener is a party, which reaches him through some path other than the sidetone path or the main channel of communication. If the delay of the echo is sufficient, a distinct repetition of the sound is heard which produces a sensation similar to the one usually associated with the word echo in common parlance. If the delay is very small the echo tends to merge with the sidetone or direct transmission.

[2] The minimum echo (singing, crosstalk) net loss is the smallest net loss at which a circuit, free of variations, is satisfactory with respect to echoes (singing, crosstalk).

[3] See "Telephone Transmission Over Long Cable Circuits," by A. B. Clark. (*Jour. A. I. E. E.*, January, 1923, and *Bell Sys. Tech. Jour.*, January, 1923.)

Talker echo is echo heard by the talker due to his own speech and listener echo is echo heard by the listener due to the far-end subscriber's speech. The principal effect of talker echo is to annoy and disturb the talking subscriber and perhaps to delay the conversation, but it is possible to continue talking, if necessary, despite this echo. Listener echo on the other hand may actually reduce the intelligibility but, in this case, also, the annoyance may be a considerable factor. However, the listener echo is usually less objectionable than talker echo (in circuits designed in accordance with the Bell System practice) and the following discussion will be limited to talker echo.

For a given circuit net loss and terminal return loss,[4] the absolute volume of talker echo varies with the talker volume. When there is a very long delay in a circuit, the talker echo comes back effectively separated from the outgoing speech and is objectionable if the volume of the echo is too large as compared to the circuit noise and room noise (and to some extent, perhaps, the volume of speech from the far end of the circuit). For shorter delays, the sidetone speech currents in the subscriber's set mask the echo so that it is less objectionable and the amount of masking increases as the delay decreases. In any case, the talker echo is objectionable when its volume (determined by the speech volume and the loss in the echo path) becomes too great compared to the combined masking effect of the total noise and the sidetone volume, with due regard for the fact that the sidetone currents precede the echoes.

Circuits Without Echo Suppressors

Inasmuch as the degradation of a circuit by echoes is subjective, the limitations which they place on circuit design must ultimately rest on experiments with talkers. The curve marked "No Echo Suppressor"[5] on Fig. 1[6] shows an experimental curve of the smallest permissible net loss in an echo path for satisfactory talker echo conditions. This was obtained with typical sidetone subsets on short loops, and with typical noise conditions. It is used to find the mini-

[4] The return loss expressed in decibels between any two impedances Z_1 and Z_2 is $20 \log_{10} \left| \frac{Z_1 + Z_2}{Z_1 - Z_2} \right|$. The return loss of a repeater section or circuit, etc., is assumed to mean the return loss between that repeater section or circuit, etc., and the network circuit normally used to balance it. The terminal return loss is the return loss of the terminal switching trunk, loop and subset.

[5] The other curves on Fig. 1 were obtained at a different time and under slightly different noise, etc., conditions from those under which the upper curve was obtained.

[6] The exact effect of an echo of very short delay is not known. Such an echo will tend to increase the sidetone and thus mask any echoes of longer delay which may be present. However, in order to obtain a continuous computation method and because very short echoes are not very important in computing minimum net losses, the curves on Fig. 1 are drawn down to zero as shown. This matter and other matters in connection with echoes are being investigated further.

mum echo net loss of a four-wire cable circuit as follows: Assume a trial net loss and compute the loss in the echo path by adding the loss from the toll switchboard to the point where the echo is reflected

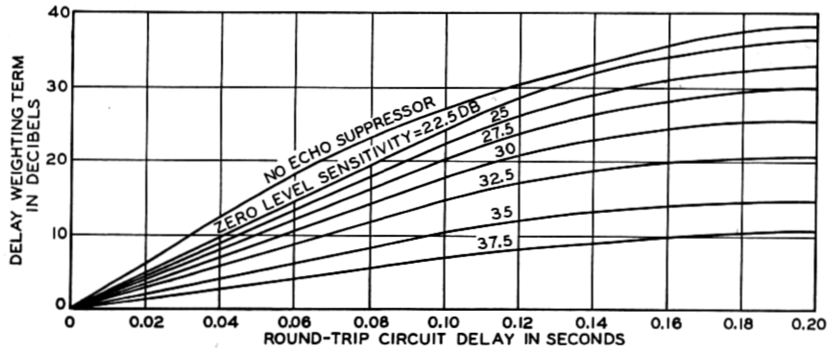

Fig. 1—Talker echo delay terms for 4-wire circuits—sidetone subsets.

back, the terminal return loss (assumed 6 db for echo computations in the Bell System) and the loss from that point back to the toll switchboard. From this total, subtract the "delay weighting term" from Fig. 1 for the corresponding round trip delay. If the resulting weighted echo path loss is greater than or equal to zero, the circuit will be satisfactory from an echo standpoint at this net loss without variations.

In the case of two-wire circuits, the echo limitations are similar to those for four-wire circuits except that echoes are also returned from intermediate points in the circuit through the return paths at the repeater hybrid coils.

The general method of determining whether circuits are satisfactory from an echo standpoint has been discussed in the paper entitled "Telephone Transmission Over Long Cable Circuits" by A. B. Clark [3] and later in a paper entitled "Echo Suppressors for Long Telephone Circuits," by A. B. Clark and R. C. Mathes (*A. I. E. E. Jour.*, June, 1925). It may be outlined briefly as follows: Determine the weighted loss of each echo path by determining the actual loss from and to the toll switchboard at the talker end (including the return loss at the point where the echo is reflected back) and then subtract the "delay weighting term" corresponding to the delay of each path as obtained from the upper curve on Fig. 1. If any one of these weighted echo path losses is reduced below zero db, the echo conditions will be unsatisfactory without regard to the effect of the other paths, as outlined above. However, if all these losses are positive, it is considered that the net effect of all of the paths may be determined by adding the power ratios (less than unity for a loss greater than zero) of the individual weighted losses together and finding the equivalent weighted echo path corresponding to this sum. When this equivalent path becomes zero db (a power ratio of 1.0), the circuit (without variations) is considered to be just satisfactory from an echo standpoint.

The distribution of gains between the different repeaters in a two-wire circuit usually has an appreciable effect upon the minimum net loss which may be obtained for a given circuit. If the gain in each direction of transmission of each repeater is equal to the loss of the preceding repeater section (or is less than it by a fixed amount called the taper), it may be shown that the echo limitations computed as above are completely determined by the delays involved, the taper, the terminal return loss and by the differences between the return loss, S, and attenuation loss, L, of the repeater sections, i.e., the values of S-L.[7] The minimum echo net loss of any given two-wire circuit (for given terminal conditions), therefore, is determined by the delays, S-L, the taper and the number of repeater sections. The value of S-L which is of the greatest importance is usually that in the important echo range, i.e., about 500 to 1,500 cycles.

While the terminal return loss is taken as a fixed value (6 db) in these computations, the return loss at intermediate repeater points varies according to the structure of the line. The statistical distribution of the return losses of loaded cable circuits may be computed as outlined by Crisson.[8] It is customary to compute the return loss, S_L, at 1,000 cycles, using the distribution function $S_F = 0$ in Crisson's formulas. To determine the echo limitations, the value $S_M = S_L - 4$ is used, principally to take into account the fact that the computed values of S_L are at a single frequency.

In addition to the return loss of the bare cable facilities, the return loss of the repeating coils and other office equipment and the effect of the termination at the far end of the repeater section must be considered. These components are:

$$S_1 = S_M + 2C,$$
$$S_2 = S_C,$$
$$S_3 = S_T + 2L + 2C,$$

where S_1, S_2 and S_3 are the return losses (attenuated to the repeater),

[7] In the following, this is assumed the same for each repeater section. It may be seen that the use of S-L instead of S and L separately effectively removes one variable from computations.

[8] "Irregularities in Loaded Telephone Circuits," by George Crisson, *B. S. T. J.*, Vol. IV, and *Elec. Comm.*, Vol. 4, October, 1925. Specific values of the deviations from which S_H may be computed are given in a paper entitled "Long Distance Telephone Circuits in Cable," by A. B. Clark and H. S. Osborne.

respectively, of the bare cable, the near-end apparatus and the terminating effect at the far end of the repeater section.

C = apparatus loss at near end.

S_C = return loss of apparatus at near end.

S_T = terminating effect of repeater and apparatus at far end of repeater section.

L = loss of the line section at 1,000 cycles.

The overall return loss of the complete repeater section, S, is assumed equal to the combination of S_1, S_2 and S_3 as the sum of the corresponding power ratios.

Circuits With Echo Suppressors

When echoes would otherwise be objectionable on a circuit, it may be equipped with an echo suppressor. On a four-wire circuit equipped with an ordinary echo suppressor, the currents which are strong enough to operate the echo suppressor have their echoes suppressed. When currents are too weak to operate the suppressor, echoes will be returned, but, of course, will be much weaker than the loudest echoes on the same circuit without an echo suppressor. The echoes on the circuit with an echo suppressor will, therefore, generally be less objectionable than those on the same circuit without an echo suppressor, since those which get back to the talker are weaker in absolute volume, while the noise and sidetone volume for a given speech volume are unchanged.

The more sensitive the echo suppressor is made, the weaker the sounds will be which will just fail to operate the suppressor. Consequently, the echoes will become less objectionable as the sensitivity is increased. However, if the sensitivity is increased too much, the suppressor may be falsely operated by noise currents, either from the circuit, from room noise at the subscriber's premises which is picked up through his transmitter, or from room noise picked up through operators' sets.

The process of determining the minimum echo net loss of a circuit equipped with an echo suppressor has the following two steps: (1) determine the zero level sensitivity [9] of the echo suppressor on the circuit which is allowable with little or no false operation from noise and (2) determine the minimum net loss from experimental curves.

[9] The zero level sensitivity is defined as the amount of loss it is necessary to insert between a 600-ohm source of one milliwatt of power and the 600-ohm input of the circuit on which an echo suppressor is located in order to cause the echo suppressor to be just operated. Unless otherwise specified, this is assumed to be at 1,000 cycles.

First, determine the maximum amount of noise (including room noise and the effect of variations in net loss) which may be expected at the echo suppressor input in an appreciable number of cases. If this noise is N db above reference noise,[10] it has been determined experimentally that the local sensitivity [11] which will cause the echo suppressor to be steadily and completely operated is about (90-N) db. Providing a reasonable margin against noise operation to allow for different kinds of noise and the like, the safe local sensitivity is about (80-N) db.

The value so determined is the maximum allowable local sensitivity. From this value, the maximum allowable zero level sensitivity is obtained by adding the gain from the circuit input to the echo suppressor input under the net loss conditions for which the local sensitivity was computed. The average allowable zero level sensitivity is less than the maximum allowable zero level sensitivity by the negative variations in net loss and echo suppressor sensitivity (the negative variations are the amount by which the average loss is decreased) which may be expected. In the Bell System, average zero level sensitivities of about 31 db on toll circuits may be considered typical.

To compute the minimum net loss on a four-wire circuit, assume a trial net loss and determine the loss in the echo path as outlined above for circuits without echo suppressors. From this loss, subtract a delay weighting term from Fig. 1 for the corresponding round trip circuit delay on the proper curve. With an echo suppressor near the center of the circuit,[12] the delay weighting term is read on the curve for the average zero level sensitivity. As before, if the resulting weighted echo path loss is greater than or equal to zero, the circuit (without variations) will be satisfactory from an echo standpoint.

In general, echo suppressors on two-wire circuits have not been found desirable in the Bell System. However, a layout of considerable interest occurs when a two-wire circuit is connected in tandem with a four-wire circuit equipped with an echo suppressor. The computation of the echo limitations is approximately as outlined above

[10] Reference noise is equal to one micro-microwatt (10^{-12} watt) at 1,000 cycles or the equivalent weighted power at other frequencies or combinations of frequencies.

[11] The local sensitivity is defined as the amount of loss it is necessary to insert between a 600-ohm source of one milliwatt of power and a 600-ohm resistance across which an echo suppressor is bridged in order to cause the echo suppressor to be just operated. Unless otherwise specified, it is assumed to be at 1,000 cycles.

[12] In the Bell System, echo suppressors are generally located near the center of the circuit. If the echo suppressor were not near the center of the circuit, due allowance for the relative variations of the zero level sensitivity and the circuit net loss should be made. For example, for an echo suppressor at the end of a circuit, the zero level sensitivity as measured from the far end would be practically a maximum when the lowest net loss was obtained.

for two-wire circuits without echo suppressors, except that the delay weighting terms for all echo paths which are acted upon by the echo suppressor are determined from the curve for the proper zero level sensitivity. The paths which are not affected by the echo suppressor are all paths which do not pass through the suppressor and any paths with enough delay beyond the suppressor so that the hangover [13] is insufficient to suppress the echo. (Echoes in this latter class are normally not obtained, since the hangover is made large enough to suppress all echoes beyond the suppressor.)

Singing and Circulating Currents

Another effect which is important principally on two-wire circuits is that of singing and circulating currents. In a two-wire circuit, if the total gain around a repeater is increased sufficiently, it will become greater than the losses across the hybrid coils and singing will occur if the phase relations are right. When this occurs, the subscriber may hear the singing tone, repeaters may be overloaded, voice-operated devices on connecting circuits may be falsely operated and other circuits in the same cable may be made noisy by cross-induction.

Even when actual singing does not occur, if the loss minus the gain around a circulating path is small, the voice currents may be considerably distorted due to the feedback currents around the repeater. If the singing margin [14] becomes small, the circulating current or "near-singing" effect is quite objectionable.

In order to provide against this possibility, it has seemed desirable in the Bell System to require a 10 db singing margin [14] around the most critical repeater in any long circuit, under average conditions of temperature, regulation, net loss, etc., and with 5 db terminal return losses. (For circuits equipped with only one or two repeaters, 8 db margin is considered sufficient.) In a similar manner to that outlined above for echoes on two-wire circuits, the quantity *S-L*, the taper, and the terminal return loss are the important things in determining this singing margin. In this case, of course, the delay does not have any large effect. The value of *S-L* which is usually of the most importance is the one at about the highest frequency efficiently transmitted, since this usually tends to be the lowest value of *S-L* within that range.

The process of computation of the singing margin around a given

[13] This is the same as the "releasing time" discussed in the paper entitled "Echo Suppressors for Long Telephone Circuits" mentioned above.

[14] The singing margin is the sum of the additional gains in the two directions which may be inserted at the most critical repeater in the circuit before singing starts, under specified conditions as to the terminations, etc.

repeater is as follows: The active return loss [15] in one direction, say east of the repeater under consideration, is first obtained (Fig. 2). The passive return loss of the adjacent repeater section toward the

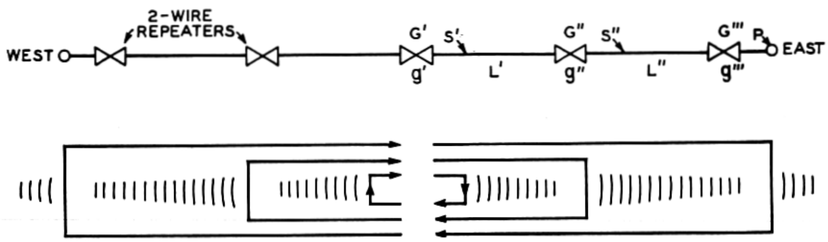

Fig. 2—Singing paths in a 2-wire circuit.
S' and S'' are passive return losses of cable sections.
P is the terminal return loss.
G', G'' and G''' are west to east gains.
g', g'' and g''' are east to west gains.

east (S') constitutes the first singing path and is determined as outlined above in considering echoes on two-wire circuits, except that the 4 db is not subtracted because singing occurs at only one frequency and because approximately the worst frequency is selected for computations. The passive return loss in the repeater section on the far side of the next repeater to the east (S'') is amplified and attenuated through the intervening gains ($G'' + g''$) and losses ($2L'$) to obtain the second component, which is $L' - G'' + S'' - g'' + L'$. Similar components are determined for all other repeater sections to the east of the one under consideration. (In the case of the circuit shown on Fig. 2, there are no more such paths.) These paths are then combined by adding the power ratios corresponding to these paths. The loss of the resultant singing path is the active return loss from the repeater under consideration with no currents returned from beyond the terminal repeater (or from the circuit terminal if there is not a terminal repeater). This active return loss is then combined with the path including the terminal repeater, viz., $(L' - G'' + L'' - G''' + P - g''' + L'' - g'' + L')$, according to the sum of their current ratios to obtain the active return loss (toward the east from the repeater in question) of the circuit in normal operating condition. (The use of current ratios rather than power ratios in this case is indicated by theoretical considerations and confirmed by experimental data.)

The active return loss toward the west from the repeater in question

[15] An active return loss is a return loss with gain inserted in the paths of one or more of the returned currents. The passive return loss is the return loss without any currents returned from beyond the adjacent repeater (or other termination if there is not a repeater there).

is then determined in a similar manner. The sum of these two active return losses minus the two-way gain of the repeater in question is approximately the singing margin around that repeater.

Whatever singing margin is obtained under average conditions, there will be certain factors tending to reduce this margin while the circuit is in normal operation. These factors include net loss variations, transmission-frequency characteristic deviations, removal of one of the normal terminations for short intervals, gain lumping due to pilot wire regulation, and slight troubles which have not yet been corrected. Because of those factors, and because of the disadvantages of near singing, 10 db singing margin under average conditions (8 db for short circuits) is believed desirable in the Bell System.

Crosstalk

Net losses may also be limited by the danger of excessive crosstalk. Far-end crosstalk from circuit 1 to circuit 2, each extending from *A* to *B*, is crosstalk which manifests itself at the *B* end of circuit 2 from the speech of the subscriber at *A* on circuit 1. Near-end crosstalk from the same talker may manifest itself at *A* on circuit 2.

From a general standpoint, the crosstalk volume should be so low that no subscriber can understand what any other subscriber says on another circuit. This is desirable from the standpoint of preserving secrecy and also from the standpoint of the annoyance which may be caused by unwanted speech currents.

The assumed limitation on circuits from a crosstalk volume standpoint is that a subscriber shall have only a very small chance of hearing understandable crosstalk. This chance is determined by the distributions of the crosstalk couplings, the room noise and circuit noise, the terminal losses, the talker volumes on other circuits, and the natures of the talkers and listeners. Present data indicate that the chance of a subscriber hearing understandable crosstalk is very small in the case of two-wire cable circuits if the crosstalk conditions are such that there is not more than about one chance in 100 that any one or more of the couplings between the disturbed circuit and the various disturbing circuits shall exceed 1,000 crosstalk units (60 db loss). Further investigations of this matter and other questions in connection with crosstalk are being made.

Crosstalk in cable circuits may be either within-quad or between-quad crosstalk. Crosstalk within the quad may be phantom-to-side, side-to-phantom or side-to-side and may be divided into office crosstalk and cable crosstalk.[16] The office crosstalk is due to capacitance

[16] Specific values of the various sources of crosstalk are given in a paper entitled "Long Distance Telephone Circuits in Cable," by A. B. Clark and H. S. Osborne, *B. S. T. J.*, Vol. XI, Oct., 1932.

unbalance in the office wiring and to repeating coils, repeaters, and other office apparatus.

The crosstalk in the cable outside the office is due to loading coil unbalance, series resistance unbalance, and capacitance unbalance. Crosstalk between different quads is normally due almost entirely to capacitance unbalance.

When the complete repeater sections have been installed, cross-connection of the circuits at certain repeater points is generally used to reduce the overall crosstalk between circuits. In the case of two-wire circuits, this cross-connection consists of breaking up all phantom-to-side and side-to-side combinations in a given quad at each repeater station, and the system is designed to make it improbable that any two of these circuits will ever be in the same quad again. In the case of four-wire circuits, this cross-connection is resorted to only at the ends of each pilot wire regulator section.

The method of computing the crosstalk limitations of a given cable circuit is as follows: Determine the r.m.s. (root mean square) within-quad crosstalk coupling per loading section by adding together the r.m.s. crosstalk coupling due to capacitance unbalance, resistance unbalance and loading coil unbalance as the r.s.s. (root sum square) of the parts expressed in crosstalk units. From this, get the r.m.s. unamplified crosstalk coupling per repeater section by properly attenuating the crosstalk coupling from each loading section. The attenuation in each case equals the loss from the output of the repeater transmitting into the disturbing circuit (in that repeater section) to the point of crosstalk coupling plus the loss from this point to the input of the repeater receiving from the disturbed circuit. The total r.m.s. within-quad crosstalk coupling per repeater section is the r.s.s. of the crosstalk coupling from each of the loading sections and from the office. The between-quad crosstalk coupling per repeater section is obtained in a similar manner.

In the case of near-end crosstalk on two-wire circuits, the unamplified crosstalk coupling so determined is then amplified or attenuated by the gains or losses from the transmitting terminal of the disturbing circuit to the repeater section in question and then to the receiving terminal of the disturbed circuit. Next, the r.s.s. of this crosstalk coupling and the between-quad crosstalk coupling from the same disturbing circuit in other repeater sections is obtained. The probability of this total crosstalk coupling exceeding 1,000 units is then determined, making due allowance for the variations of net loss. For near-end crosstalk, in a circuit without variations, the probability that 1,000 units of crosstalk will be exceeded when the total r.m.s. crosstalk coupling[17] is "x" crosstalk units is approximately

$$P_n = e^{-k^2} \text{ where } k = \frac{1{,}000}{x} .$$

An approximate method of allowing for circuit variations is to consider a circuit with variations equivalent to a circuit without variations with a net loss smaller than the average net loss of the former circuit by one-quarter of the variations; i.e., if the variations are $\pm V$ db, the value of k to be used in the above formula is

$$k = \frac{1{,}000}{x} 10^{-(V/80)} .$$

Fig. 3 shows the value of P_n plotted against k.

When these probabilities have been determined for all circuits having a similar within-quad exposure to the circuit under consideration, the total probability of the crosstalk coupling exceeding 1,000 units from any circuit may be determined and is approximately the sum of the probabilities of excessive crosstalk coupling from each of the disturbing circuits. (The probability of excessive crosstalk from circuits not having within-quad exposures is considered negligible.) When this probability is .01, the circuit is considered just satisfactory from a crosstalk standpoint.

Far-end crosstalk coupling is computed in a similar manner, using the probability relations applying to far-end crosstalk and four-wire circuits, which are somewhat different from those applying to near-end crosstalk and two-wire circuits. In this case, the probability of exceeding 1,000 units of crosstalk when the r.m.s. total crosstalk is "x" units is approximately

$$P_f = 1 - \frac{2}{\sqrt{\pi}} \int_0^{k/\sqrt{2}} e^{-t^2} dt, \text{ where } k = \frac{1{,}000}{x} ,$$

or with variations of $\pm V$ db,

$$k = \frac{1{,}000}{x} 10^{-(V/80)} .$$

Fig. 3 shows P_f plotted against k.

Variations

When the minimum net loss at which a circuit will be satisfactory has been determined, or when the minimum working net loss is com-

[17] The ratio of the average near-end crosstalk to the r.m.s. near-end crosstalk is about $\sqrt{\pi}/2$. The similar ratio for far-end crosstalk is $\sqrt{2}/\sqrt{\pi}$.

puted directly, it is necessary to make an allowance for the fact that the circuit will vary from time to time. The principal variations in an unregulated cable circuit are caused by temperature changes. In

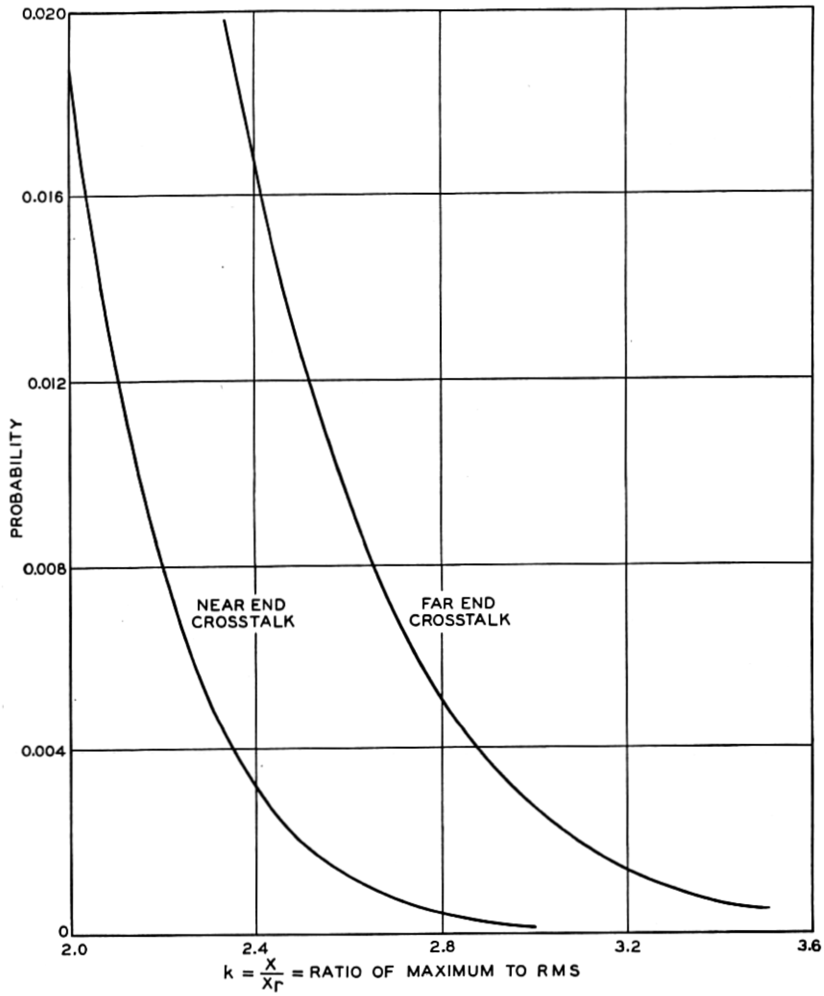

Fig. 3—Probability of exceeding a maximum of X crosstalk units when the R.M.S. is X_r crosstalk units.

a 1,000-mile circuit of 19-gauge H-44-25 four-wire facilities in aerial cable in the northeastern part of the United States, for example, a variation at 1,000 cycles of about ± 55 db from the average would be normally expected due to temperature variations throughout a year. About 35 to 45 per cent of this would occasionally occur in one day while in shorter circuits somewhat higher percentages might be encountered. In underground cable about one third as much would be encountered in a year, but very little would normally occur in one day since the rate of change is small.

In order to take care of these large variations a system of pilot wire regulation is used. The following discusses this system in some detail in order to show what the residual variations are. This system consists of a pilot wire extending through the cable whose circuits are to be regulated, each pilot wire being perhaps 100 to 150 miles in length. An automatic mechanism measures the d-c. resistance of this pilot wire frequently, and makes occasional adjustments of the gain of the regulating repeaters. In the case of the four-wire facilities referred to above, these adjustments are made in approximately .5 db steps at 1,000 cycles, and other suitable adjustments are made at other frequencies.

This pilot wire is placed in the four-wire part of the cable (it is usually obtained by compositing a four-wire circuit) and therefore has very closely the same temperature variation as the four-wire pairs. The position in the cable of the two directions of transmission of four-wire circuits is reversed [18] at the center of each repeater section, so it is possible to regulate both directions of transmission from a pilot wire in either group without serious error. Since the two-wire circuits are comparatively short, have generally smaller variations in decibels per mile than four-wire circuits, and usually have an average position in the cable, there is no serious error in regulating these from the same pilot wire.

Due to the finite steps in which these regulators operate, there is a residual variation which is approximately $\pm .25$ db per regulating repeater. In addition, there may be a certain amount of lag in the operation of these regulators, because of the fact that it is desirable to prevent excessively frequent operation of these devices, and perhaps partly because of mechanical backlash. To prevent hunting it is necessary to make the adjustment in the pilot wire regulator somewhat smaller than the adjustment which would be necessary to make all the variation due to this cause a random matter. In other words, when the temperature is changing in a given direction in many repeater sections, for example early in the morning, the adjustment at each of the pilot wire regulators is slightly behind what it theoretically should be for the pilot wire resistance obtaining at that time. This results in a directly additive effect in all regulating repeaters in a given circuit during certain times of day. By careful design and routine

[18] This assumes concentric segregation which is generally used.

maintenance, it is possible to reduce this effect to about ±.03 db per regulating repeater. Other regulation inaccuracies, including imperfections in the design and manufacture of regulating networks and departure of individual pairs from average characteristics, may introduce an additional error of about ±.1 db per regulator, this effect being more or less random, however.

In addition to the residual effects of temperature changes there are variations in the net losses of the circuits due to repeater battery changes and humidity changes. The repeater batteries are usually held to fairly narrow limits and vacuum tubes are tested regularly for emission. The expected change in repeater gain due to an "A" battery change of ±.5 volt is about ±.2 db and for a "B" battery change of ± 5.0 volts is about ±.25 db.

In office cabling and in the switchboard multiple at the terminals of the circuit there may be a considerable amount of variation due to changes in the humidity. This has been largely taken care of by improvements in the type of cable used (cellulose acetate) and by keeping the lengths of office cable as short as possible. However, a residual variation of about ±.5 db may be expected, a considerable part of which is due to switchboard multiple.

If the number of repeaters in a circuit is "n" and the number of regulators is "r," the total variations are considered to be about

$$V_1 = \pm \sqrt{(.5 + .03r)^2 + (.25)^2 r + (.1)^2 r + (.2)^2 n + (.25)^2 n}.$$

These items are allowances respectively for humidity variations, regulator lag, finite regulator steps, other regulator errors, "A" battery changes and "B" battery changes. Rearranging the equation,

$$V_1 = \pm \sqrt{.25 + .1025r + .0009r^2 + .1025n}.$$

In addition to this variation, the probability that the average net loss of a given circuit is not exactly as specified must be considered, so the variation from the specified value is considered to be about $\sqrt{2}\,V_1$ or

$$V_2 = \pm \sqrt{.5 + .205r + .0018r^2 + .205n}.$$

Assuming that each of the individual variations from the various sources has an equal probability throughout its range, the probability that the overall variation V_2 will be exceeded is about .085, and the probability that the average variation in the two directions of transmission (which is of considerable interest in singing or echo computations) will exceed this is still smaller.

Example

As an example of the general procedure in specifying satisfactory net losses for terminal circuits, consider a 500-mile 19-gauge H-44-25 four-wire cable circuit not equipped with echo suppressors. From the information in the paper by A. B. Clark and H. S. Osborne referred to above:

1. The minimum echo net loss is about 4.5 db.
2. The transmission variations are about ± 2 db.
3. Therefore, the minimum working echo net loss is about 6.5 db.
4. The minimum working crosstalk net loss is about 6.6 db.
5. The minimum working singing net loss is about 0 db.
6. Therefore, the minimum working net loss of the circuit is about 6.6 db.

It will, therefore, be satisfactory to specify 6.6 db with normal variations of ± 2.0 db for the circuit in question.